Katophorite from the Jade Mine Tract, Myanmar: mineral description of a rare (grandfathered) endmember of the amphibole supergroup

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ABSTRACT

Katophorite has the ideal formula ^ANa^B(NaCa)^C(Mg₄Al)^T(Si₇Al)O₂₂^W(OH)₂ (Hawthorne *et al.*, 2012). No published analyses of amphiboles fall in the katophorite compositional field, except that of Harlow and Olds (1987) for an amphibole from near Hpakan in the Jade Mine Tract, Myanmar. This amphibole was approved by the International Mineralogical Association Commission on New Minerals, Nomenclature and Classification (vote 2013-140) as katophorite, and is reported here. Holotype katophorite is monoclinic, space group C2/m, a = 9.8573(8), b = 17.9617(15), c = 5.2833(4) Å, $\beta = 104.707(2)^{\circ}$, V =904.78(13) Å³, Z = 2. The calculated density is 3.091 g cm⁻³. In plane-polarized light, katophorite is pleochroic, X = pale blue (medium), Y = light blue-green (strongest), Z = colourless; $X \land a = 30.6^{\circ}$ (β obtuse), $Y \parallel b$, $Z \land c = 15.8$ (β acute). It is biaxial negative, $\alpha = 1.638$, $\beta = 1.642$, $\gamma = 1.644$, all ± 0.002 ; $2V_{obs} = 73(1)^\circ$, $2V_{calc} = 70^\circ$. The eight strongest lines in the powder X-ray diffraction pattern are [d in Å (I)(hkl)]: 2.700 (100)(151), 3.129 (69)(310), 2.536 (65)(202), 3.378 (61)(131), 8.421 (55)(110), 2.583 (46)(061), 2.942 (43)(221) and 2.334 $(41)(\overline{3}51)$. Electron-microprobe analysis of the refined crystal gave SiO₂ 51.74, Al₂O₃ 7.38, TiO₂ 0.14, FeO 1.55, Fe₂O₃ 2.82, MgO 18.09, CaO 8.17, Na₂O 6.02, K₂O 0.24, F 0.06, H₂O_{calc} 1.80, Li₂O_{calc} 0.09, sum 100.55 wt.% (Li₂O and H₂O based on the results of single-crystal structure refinement). The formula unit, calculated on the basis of 24 (O,OH,F) with (OH + F + O) = 2 is: $\stackrel{A}{(Na_{0.85}K_{0.04})_{\Sigma=0.89}} \stackrel{B}{(Ca_{1.22}Na_{0.78})_{\Sigma=2.00}} \stackrel{C}{(Mg_{3.76}Al_{0.43}Fe_{0.30}^{3+}Cr_{0.27}^{3+}Fe_{0.18}^{2+}Li_{0.05}Ti_{0.01}^{4+})_{\Sigma=5.00}}{(Si_{7.21}Al_{0.79})_{\Sigma=8.00}O_{22}} \stackrel{W}{(OH)_{1.67}O_{0.30}F_{0.03}}]_{\Sigma=2.00}.$

Keywords: katophorite, amphibole, electron-microprobe analysis, crystal-structure refinement, Jade Mine Tract, Myanmar.

Introduction

THE recent International Mineralogical Association (IMA) report on amphibole nomenclature and classification (Hawthorne *et al.*, 2012) re-defined the unit formula of all ^B(NaCa) amphiboles to their ^CAl-dominant compositions. In particular, katophorite changed from

* E-mail: oberti@crystal.unipv.it DOI: 10.1180/minmag.2015.079.2.13 $\label{eq:analytic_state} \begin{array}{l} {}^{A}Na^{B}(NaCa)^{C}[Mg_{4}(Al,Fe^{3+})]^{T}(Si_{7}Al)O_{22}{}^{W}(OH)_{2} \\ to {}^{A}Na^{B}(NaCa)^{C}(Mg_{4}Al)^{T}(Si_{7}Al)O_{22}{}^{W}(OH)_{2}. \\ Rootname katophorite (and its Fe^{2+} analogue \\ \end{array}$

Rootname katophorite (and its Fe^{2+} analogue ferro-katophorite) was introduced by Brøgger (1894) based on the Greek word κατώφορος (having a downward tendency), which refers to the measured optical properties that helped to identify it with respect to arfvedsonite and hornblende. The samples described by Brøgger (1894) are strongly zoned from katophorite to arfvedsonite. Indeed, the reported chemical

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analysis (SiO₂ 43.5, Al₂O₃ 4.5, MgO 1.5, Fe₂O₃ 5.5, FeO 30.5, CaO 5.0, Na₂O 7.0, K₂O 1.5 wt.%), when re-calculated based on 24 O atoms (H₂O = 1.90, total 100.9 wt.%), gives Na_{2.17}K_{0.31} Ca_{0.86}Fe⁴_{4.08}Mg_{0.36}Ti_{0.12}Fe³⁺_{0.66}Al_{0.86}Si_{6.96} O₂₂(OH)_{1.90}, a formula somewhat problematic from a crystal-chemical point of view because it has (1) a very large sum of cations per formula unit (16.38), well beyond the stoichiometric limit of 16 and involving excess A+B cations; and (2) the presence of Fe³⁺ or Ti⁴⁺ as T cations, which is contrary to current evidence (Oberti *et al.*, 2007). However, the composition approximates to 'ferro-ferri-katophorite' (with a component of arfvedsonite).

Compositional data (Deer *et al.*, 1963) for katophorite from the Shields River basin, Montana (USA), results in a ferri-katophorite with a significant oxo component: $(Na_{0.59}K_{0.41})$ $(Na_{1.12}Ca_{0.88})(Mg_{3.24}Fe_{1.16}^{2+}Fe_{0.45}^{3+}Al_{0.26}Ti_{0.14}$ $Mn_{0.02})_{\Sigma=5.27}(Si_{7.12}Al_{0.88})O_{22}(OH)_{1.44}$, although significant violation of the amphibole stoichiometry would suggest a further check or a different recalculation.

The list of IMA-approved minerals (http:// nrmima.nrm.se/, accessed March 2015) summarizes the situation in the katophorite compositional field: (1) katophorite: grandfathered (Brøgger, 1894); (2) ferro-katophorite: grandfathered (Brøgger, 1894; Mandarino, 1998); (3) ferri-katophorite: named (Pushcharovski et al., 2003). The formula proposed by Pushcharovski *et al.* (2003), i.e. ^A(Na_{0.87}K_{0.13}) ^B(Na_{1.18}Ca_{0.82})^C($^{M(1)}$ (Mg_{1.41}Fe³⁺_{0.42}Ti_{0.17}) ^{M(2)}(Fe³⁺_{1.31}Mg_{0.69})^{M(3)}(Mg_{0.60}Fe²⁺_{0.38}Mn_{0.02})) ^T($^{T(1)}$ (Si_{3.16}Al_{0.84})^{T(2)}Si₄)O₂₂^W(O_{1.05}OH_{0.66}F_{0.29}), does conform to amphibole stoichiometry but has major crystal-chemical problems because the sum of the highly-charged cations at the M(1) and M(3)sites does not compensate for the oxo component. Moreover, after Hawthorne et al. (2012), this composition must be considered as an oxo amphibole ('oxo-ferri-katophorite') because O^{2-} is the dominant W anion. However, there has been no formal approval of this species. The composition for katophorite reported in the Handbook of Mineralogy (Anthony et al., 2001), with "strange" (incompatible?) unit-cell parameters and optics might also be placed in the compositional field of oxo amphiboles; (4) ferri-fluoro-katophorite: named after Hawthorne et al. (2006), proposal in preparation.

Recently, Ali and Arai (2013) reported analyses of zoned crystals of Cr-rich (up to 3.1 wt.% oxide)

"magnesiokatophorite" (i.e. katophorite after Hawthorne *et al.*, 2012) in hydrous mantle xenoliths from Yemen. Interestingly, these authors concluded that this phase "formed through metasomatism by Na-rich carbonatite melt" and is "an indicator of metasomatism by hydrous Na-rich carbonatite in the upper mantle".

To summarize, there is a need to put some order in the katophorite compositional space, to check the available data and to provide a reliable mineralogical characterization of katophorite itself. In this paper, we provide the complete mineralogical characterization of katophorite from the Jade Mine Tract, Myanmar, from the collection of the American Museum of Natural History, New York (approved by the IMA Commission on New Minerals, Nomenclature and Classification as IMA 2013-140, Oberti *et al.*, 2014). This sample was first described by Harlow and Olds (1987) who focused mainly on ureyite (NaCrSi₂O₆) and ureyitic pyroxenes.

Occurrence and paragenesis

The holotype material of katophorite was found near Hpakan, Jade Mine Tract, Kachin State, Myanmar. The sample was acquired from a mineral dealer in 1959. The specimen is a small rock sample and resides in the mineral collections of the American Museum of Natural History, catalogue number AMNH H32734 (Fig. 1). The refined and analysed crystal described in this work has the code 1211 in the amphibole database of the CNR-IGG Pavia.

Associated minerals are kosmochlor-jadeite solid solution, omphacite, chromite, banalsite,



FIG. 1. The rock specimen from which the mineral was extracted.

clinochlore and other amphibole species. Mixtures of amphibole and kosmochlor-rich pyroxene are inferred to form as an amphibole-dominant reaction boundary between jadeitite veins and altering peridotite. Chromium enrichment is associated with veins cutting chromite-bearing or chromitite pods within the ultramafic assemblage, as at locations like Maw-Sit-Sit, in the northern part of the Jade Mine Tract ultramafic body (Harlow and Olds, 1987; Mével and Kiénast, 1986; Hughes *et al.*, 2000; Shi *et al.*, 2012).

Appearance and physical and optical properties

The sample is variegated dark emerald green in colour with black spots (chromite) and is crosscut by white veins (banalsite). Amphibole is both coarsely crystalline to several mm in length, although mosaicked, and forms fine mesh intergrowths. Pyroxene grains tend to form in clusters surrounding amphibole along what appear to be shear boundaries within the sample.

Katophorite is pale blue in colour; the lustre is vitreous, transparent and fluorescence is not present. The tenacity is brittle and single crystals show a perfect cleavage parallel to {110}. The density (calculated from the unit formula and cell dimensions) is 3.091 g cm^{-3} . A spindle stage was used to orient a crystal for measurement of refractive indices and 2V by extinction curves (Bartelmehs et al., 1992). The optical orientation was determined by transferring the crystal from the spindle stage to a single-crystal diffractometer and measuring the relative axial relations by X-ray diffraction. In transmitted light, katophorite is pleochroic X = pale blue (medium), Y = light blue-green (strongest), Z = colourless (minimum), $X \wedge a = 30.6^{\circ}$ (β obtuse), $Y \parallel b$, $Z \wedge c = 15.8$ $(\beta$ acute). It is biaxial negative with indices of refraction $\alpha = 1.638$, $\beta = 1.642$, $\gamma = 1.644$ all ± 0.002 measured with gel-filtered Na light ($\lambda = 589.9$ nm); $2V_{obs} = 73(1)$, $2V_{calc} = 70^{\circ}$.

X-ray diffraction and crystal-structure refinement

The crystal selected for data collection and structure refinement was ~180 μ m × 100 μ m \times 50 µm in size. Data collection was carried out on a Bruker-AXS Smart-Apex CCD-based diffractometer with graphite-monochromatized MoK α X-radiation ($\lambda = 0.7107$ Å). Omegarotation frames (scan width 0.3°, scan time 20 s, sample-to-detector distance 50 mm) were processed with the SAINT software package (Bruker, 2003) and intensities were corrected for Lorentz and polarization effects; absorption effects were evaluated empirically by the SADABS software package (Sheldrick, 1996) and an absorption correction was applied to the data. Accurate unit-cell dimensions were calculated by least-squares refinement of the positions of 3110 reflections with $I > 10 \sigma(I)$ in the 2 θ range 4–60°.

The 6852 collected reflections were reduced to 1370 unique reflections (mean redundancy = 5, $R_{\text{int}} = 2.3$ %). 1138 reflections with $I > 3 \sigma(I)$ were considered as observed during unweighted fullmatrix least-squares refinement on F. Scattering curves for fully ionized chemical species were used at sites where chemical substitutions occur; neutral vs. ionized scattering curves were used at the T and anion sites [except O(3)] according to the procedure described by Hawthorne et al. (1995). Full-matrix least-squares structure refinement (SREF) on $I > 3\sigma_I$ yielded $R_{obs} = 3.2\%$ and $R_{\rm all} = 3.8\%$. The unit-cell dimensions and details of the crystallographic study are reported in Table 1. Table 2 lists atom coordinates and anisotropic displacement parameters and Table 3

TABLE 1. Miscellaneous information for katophorite AMNH H32734.

b(A) (A) (7)(5) (7)(7)(7)(7)(7)(7)(7)(7)(7)(7)(7)(7)(7)(a (Å)	0.8573(8)	Crustal size (mm)	0.18 × 0.10 × 0.05
D(A) 17.9017(13) Crystal colour pare blue C(A) 5.2833(A) Total no. of reflections 6852	L(A)	9.0373(0) 17.0617(15)	Crystal size (IIIII)	$0.10 \times 0.10 \times 0.03$
$2 (\Delta)$ $10191 n0 01 reflections 583/$	(A)	5 2822(4)	Tratal and a Charting	pare blue
	2 (A)	5.2853(4)	Total no. of reflections	0852
β (°) 104./0/(2) No. unique reflections 13/0	β (°)	104.707(2)	No. unique reflections	1370
V (A ³) 904.78(13) No. observed reflections ($I > 3\sigma_I$) 1138	$V(A^3)$	904.78(13)	No. observed reflections $(I > 3\sigma_I)$	1138
Space group $C2/m$ θ range (°) $1-30$	Space group	C2/m	θ range (°)	1-30
Z 2 R_{merge} (%) 2.3	Ζ	2	R_{merge} (%)	2.3
$D_{\text{calc}} (\text{g cm}^{-3})$ 3.091 $R_{\text{obs}} (\%)$ 3.2	$D_{\text{calc}} (\text{g cm}^{-3})$	3.091	$R_{\rm obs}$ (%)	3.2
μ MoK α (cm ⁻¹) 18.9 R_{all} (%) 3.8	μ MoK α (cm ⁻¹)	18.9	$R_{\rm all}$ (%)	3.8

Site	SS	x/a	y/b	z c	B_{eq}	β^{11}	β^{22}	β ³³	β^{12}	β^{13}	β^{23}
(1)C		0.10932(18)	0.08779(10)	0.21814(35)	1.11(4)	24	11	103	-2	10	-2
O(2)		0.11900(18)	0.17088(10)	0.72951(36)	1.10(4)	22	10	114	0	6	1
0(3)	16.30(6)	0.10871(28)	0	0.71048(56)	1.28(6)	25	11	142	I	13	I
0(4)		0.36446(20)	0.24945(11)	0.79191(37)	1.29(4)	42	8	128	-4	26	-1
O(5)		0.34888(19)	0.13447(11)	0.09978(38)	1.40(4)	27	15	119	0	14	15
0(0)		0.34368(19)	0.11635(11)	0.59946(38)	1.30(4)	28	12	131	1	15	-10
0(1)		0.33896(28)	0	0.28282(57)	1.43(6)	34	6	182	I	20	I
7(1)		0.27960(7)	0.08545(4)	0.29914(14)	0.86(1)	22	7	84		11	
T(2)		0.28850(7)	0.17235(4)	0.80679(13)	0.89(1)	22	8	84		11	0
M(1)	28.64(14)	0	0.08859(6)	1/2	0.98(3)	27	6	89	Ι	16	I
M(2)	29.10(14)	0	0.17793(6)	0	1.05(3)	26	6	108	I	15	I
M(3)	13.67(6)	0	0	0	0.92(4)	25	7	84	I	11	I
M(4)	33.34(18)	0	0.27783(5)	1/2	1.31(3)	39	10	143	Ι	38	I
, P	2.70(4)	0	1/2	0	2.5(3)	51	19	330	Ι	65	I
4(m)	2.37(11)	0.0508(21)	1/2	0.1090(34)	2.6(4)	109	16	208	I	66	I
4(2)	5.65(9)	0	0.4701(4)	0	2.8(2)	75	11	509	I	141	I
H	1.54(18)	0.172(7)	0	0.738(13)	1.1						

TABLE 2. Atomic coordinates, refined site-scattering values (ss, e.p.f.u.) and atom-displacement parameters (B_{eq} , \mathring{A}^2 ; $\beta^{ij} \times 10^4$) for katophorite AMNH H32734.

e.p.f.u. - electrons per formula unit.

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gives selected interatomic distances and parameters related to the conformation of the double chain of tetrahedra. The observed structure factors have been deposited with the Principal Editor of *Mineralogical Magazine* as a cif file and are available from www.minersoc.org/pages/ e journals/dep mat.html.

The *a:b:c* ratio calculated from the unit-cell parameters is 0.549:1:0.294. A comparison between the mineral properties of this sample and of those previously reported as katophorite is given in Table 4.

The powder X-ray diffraction data (CuK α , $\lambda = 1.54178$ Å) were obtained using the *XPREP* utility of *SAINT* (Bruker, 2003) which generates a 2D powder diffractogram (Debye-Scherrer technique) starting from the F_{obs} collected on the single crystal and taking into account solely the information concerning the unit-cell dimensions and the Laue symmetry. No Lorentz and polarization corrections were applied. Data are given in Table 5.

Chemical composition

The crystal of katophorite used for the crystallographic study was embedded in epoxy and analysed by electron microprobe using a Cameca SX-100 operating in wavelength-dispersive mode with excitation voltage 15kV, specimen current 10 nA, beam diameter 5 µm, peak-count time 20 s and background-count time 10 s. The following standards and crystals were used for $K\alpha$ X-ray lines: Si: diopside, TAP; Ca: diopside, LPET; Ti: titanite, LLiF; Fe: fayalite, LLiF; Mn: spessartine, LLiF; Cr: chromite, LLiF; Mg: forsterite, LTAP; Al, andalusite, TAP; K: orthoclase, LPET; Na: albite, TAP; F: fluoro-riebeckite, LTAP; Zn: gahnite, LLiF. Data reduction was performed using the $\varphi(\rho Z)$ procedure of Pouchou and Pichoir (1985). Vanadium, Cr, Ni and Cl were below the detection limit. The average of 11 analyses is given in Table 6, together with a formula based on stoichiometric constraints and SREF results (see below for a detailed discussion).

TABLE 3. Selected interatomic distances (Å) and angles (°) in katophorite AMNH H32734.

$\begin{array}{c} T(1) - O(1) \\ T(1) - O(5) \\ T(1) - O(6) \\ T(1) - O(7) \\ < T(1) - O \end{array}$	1.624(2) 1.648(2) 1.648(2) <u>1.653(1)</u> 1.643	T(2) - O(2) T(2) - O(4) T(2) - O(5) T(2) - O(6) < T(2) - O>	1.616(2) 1.586(2) 1.657(2) <u>1.676(2)</u> 1.634
$M(1) - O(1) \times 2 M(1) - O(2) \times 2 M(1) - O(3) \times 2 < M(1) - O>$	2.048(2) 2.076(2) <u>2.076(2)</u> 2.067	$M(2)-O(1) \times 2 M(2)-O(2) \times 2 M(2)-O(4) \times 2 $	2.117(2) 2.070(2) <u>1.987(2)</u> 2.058
$M(3) - O(1) \times 4$ $M(3) - O(3) \times 2$ < M(3) - O >	2.085(2) 2.079(3) 2.083	$M(4)-O(2) \times 2 M(4)-O(4) \times 2 M(4)-O(5) \times 2 M(4)-O(6) \times 2$	2.411(2) 2.335(2) 2.752(2) <u>2.583(2)</u>
$\begin{array}{l} A-\mathrm{O}(5)\times 4\\ A-\mathrm{O}(6)\times 4\\ A-\mathrm{O}(7)\times 2\\ <\!\!A-\mathrm{O}\!\!> \end{array}$	2.954(2) 3.093(2) <u>2.441(3)</u> <u>2.907</u>	< M(4) - O > $A(m) - O(5) \times 2$ $A(m) - O(5) \times 2$	2.520 3.122(2) 2.930(2)
$\begin{array}{l} A(2) - O(5) \times 2 \\ A(2) - O(6) \times 2 \\ A(2) - O(7) \times 2 \\ < A(2) - O^{-1} \end{array}$	2.535(2) 2.758(2) <u>2.499(3)</u> 2.597	$A(m) - O(6) \times 2 A(m) - O(7) A(m) - O(7) A(m) - O(7) $	2.648(2) 2.485(3) 3.120(3) $2.571(3) 2.842$
<i>M</i> (1)– <i>M</i> (2)	3.091(1)	O(3)-H	0.61(6)
T(1) - O(5) - T(2) T(1) - O(6) - T(2) T(1) - O(7) - T(1)	135.0(1) 136.3(1) 136.5(1)	O(5)-O(6)-O(5) O(6)-O(7)-O(6)	165.8(1) 103.0(1)

	Brøgger (1894)	Anthony <i>et al.</i> (2001) from Deer <i>et al.</i> (1963)	This work, AMNH H32734
Colour		Black, dark green-black, red-brown	Pale blue
Optical class		Biaxial (–)	Biaxial (–)
Pleochroism	reddish	Strong in yellow and red-brown	α = pale blue, β = light blue-green, γ = colourless
Orientation		Y = b	$X \wedge a = 30.6^{\circ} (\beta \text{ obtuse}), Y // b,$ $Z \wedge c = 15.8 (\beta \text{ acute})$
Absorption	Y > Z > X	$Y > Z \approx X$	Y > X > Z
α		1.639-1.681	1.638(2)
β		1.658-1.688	1.642(2)
γ		1.600-1.690	1.644(2)
2V _{obs}	$30 - 60^{\circ}$	0-50°	73(1)°
a (Å)		10.019(2)	9.8573(8)
b		18.036(2)	17.9617(15)
с		5.286(3)	5.2833(4)
β (°)		104.98(3)	104.707(2)

TABLE 4. Comparison of optical and crystallographic data for katophorite AMNH H32734 and samples formerly considered as katophorite.

The unit formula based on 24 O and ${}^{W}(OH + F + O^{2-}) = 2$ atoms per formula unit (a.p.f.u.) is: ${}^{A}(Na_{0.85}K_{0.04})_{\Sigma=0.89}{}^{B}(Ca_{1.22}Na_{0.78})_{\Sigma=2.00}$ ${}^{C}(Mg_{3.76}Al_{0.43}Fe_{0.30}^{3+}Cr_{0.27}^{3+}Fe_{0.18}^{2+}Li_{0.05}Ti_{0.01}^{4})_{\Sigma=5.00}$ ${}^{T}(Si_{7.21}Al_{0.79})_{\Sigma=8.00}O_{22}{}^{W}[(OH)_{1.67}O_{-30}^{2}F_{0.03}]_{\Sigma=2.00}$. The maximum amount of the oxo component (O^{2-}) was evaluated from SREF results [in

particular, the M(1)-M(2) distance calibrated on

pargasite/kaersutite (see Oberti *et al.*, 2007 for a review on this subject). The refined site-scattering value at the M(3) site (13.67 electrons per formula unit, Table 6) is slightly lower than that expected for a normal partition of Mg and Fe²⁺ between M(1) and M(3), indicative of the presence of a small amount of Li at M(3) (see Hawthorne et *al.*, 1993, 1994; Oberti *et al.*, 2007), and this accords

TABLE 5. Powder X-ray data for katophorite AMNH H32734. The eight strongest lines are in bold.

I _{rel}	d(calc)	h k l	$I_{\rm rel}$	d(calc)	h k l	I _{rel}	d(calc)	h k l	I _{rel}	d(calc)	h k l
11	8.980	020	46	2.583	061	5	1.953	190	7	1.589	600
55	8.421	110	65	2.536	$\overline{2}$ 0 2	6	1.934	<u>3</u> 52	22	1.577	ī 5 3
2	5.070	1 3 0	2	2.457	0 2 2	9	1.896	510	8	1.557	4 0 2
24	4.881	<u>1</u> 11	2	2.441	$\bar{2}$ 2 2	5	1.876	4 61	14	1.535	ō 0 2
2	4.770	2 0 0	6	2.404	2 61	12	1.858	ī91	25	1.512	<u>2</u> 63
25	4.490	040	10	2.380	3 5 0	10	1.840	Ī72	12	1.501	551
2	4.211	2 2 0	41	2.334	351			4 4 2			4 82
7	3.990	1 1 1	20	2.289	$\bar{1}$ 7 1	4	1.817	530	14	1.497	0 12 0
15	3.870	ī 3 1	23	2.278	312	5	1.796	0 10 0	6	1.469	4 4 2
61	3.378	131	9	2.208	2 42	5	1.748	512			223
40	3.269	240	37	2.158	261	12	1.683	ī 3 3	11	1.452	ō42
69	3.129	310	5	2.129	Ī 5 2			2 82			3 11 0
6	3.027	<u>3</u> 11	20	2.046	202	10	1.674	023	34	1.438	<u>6</u> 61
43	2.942	2 2 1	27	2.016	4 0 2			<u>3</u> 91	2	1.402	621
17	2.807	3 3 0			3 5 1	27	1.649	461	13	1.366	512
36	2.732	331	6	1.997	370	9	1.634	480	8	1.360	553
100	2.700	151	3	1.969	371	12	1.609	1 11 0			

with stoichiometry. The compatibility index $(1 - K_P/K_C)$ is -0.001 (superior).

The simplified formula of katophorite is ${}^{A}Na^{B}(NaCa)^{C}(Mg_{4}Al)^{T}(Si_{7}Al)O_{22}^{W}(OH)_{2}$, which requires SiO₂ 51.30, Al₂O₃ 12.44, MgO 19.66, CaO 6.84, Na₂O 7.56, H₂O 2.20, total 100.00 wt.%.

Crystal chemistry and discussion

Site populations (Hawthorne *et al.*, 1995) were calculated based on present knowledge of amphibole crystal chemistry and are reported in Table 7. ^TAl is ordered at the T(1) site (Oberti *et al.*, 1995, 2007; Hawthorne and Oberti, 2007). As far as high-charge cations are concerned, the pattern of refined mean bond lengths shows that the amount of Fe³⁺ required to balance the oxo component at the O(3) oxygen atom is almost completely ordered at the M(1) site. The other high-charged cations are ordered at the M(2) site. Holotype katophorite is enriched in Cr³⁺

(0.27 a.p.f.u.). This feature is also present in the

only other katophorite sample described by Ali and Arai (2013) from Yemen xenoliths, and might suggest crystal-chemical or geochemical constraints for the crystallization of katophorite. As expected in ^B(NaCa) amphibole compositions with little or no F, the A cations distribute between the two different subsites A(m) and A(2)within the A cavity (Hawthorne *et al.*, 1996).

Katophorite is related to eckermannite and magnesio-arfvedsonite (the other amphibole endmembers found recently in the Jade Mine Tract (Oberti *et al.*, 2015*a*,*b*) by the coupled heterovalent substitution $^{M(4)}$ Ca $^{T(1)}$ Al $^{M(4)}$ Na $^{T(1)}$ Si $_{-1}$ and the homovalent substitution $^{M(2)}$ Fe $^{3+M(2)}$ Al $_{-1}$. Both the samples reported so far are enriched in Cr $^{3+}$, which is not present in eckermannite and magnesio-arfvedsonite, and presumably substitutes for Fe $^{3+}$ and Al. Another interesting feature is the frequent indication that this amphibole composition, as well as its counterparts enriched in Fe $^{2+}$ and Fe $^{3+}$, have a significant or even dominant oxo-component,

Oxide	Wt.%		a.p.f.u.
SiO ₂	51.74(72)	Si	7.214
TiO ₂	0.14(01)	Al	0.786
Al_2O_3	7.38(59)	Sum T	8.000
Cr_2O_3	2.48(12)	Ti ⁴⁺	0.015
Fe ₂ O ₃ *	2.82	Al	0.427
FeO	1.55	Cr ³⁺	0.273
FeO _{TOT}	4.09(31)	Fe ³⁺	0.296
MgO	18.09(33)	Fe ²⁺	0.181
CaO	8.17(78)	Mg	3.757
Na ₂ O	6.02(64)	Li	0.050
K ₂ O	0.24(01)	Sum C	4.999
Li ₂ O**	0.09	Na	0.779
H ₂ O***	1.80	Ca	1.221
F	0.06(06)	Sum B	2.000
-O=F	-0.03	Κ	0.043
Total	100.55	Na	0.848
		Sum A	0.891
Site scattering (e.p.f.u.)	OH	1.674
	calc. obs.	F	0.026
С	70.07 71.40	O^{2-}	0.300
В	32.99 33.34	Sum W	2.000
А	10.15 10.73		

TABLE 6. Chemical composition and unit formula (based on 24 anions) for katophorite AMNH H32734.

* FeO:Fe2O3 ratio calculated from single-crystal structure-refinement results;

** calculated taking into account stoichiometric constraints;

*** calculated based on 24 (O, OH, F) with (O, OH, F) = 2 a.p.f.u.

e.p.f.u. - electrons per formula unit; a.p.f.u. - atoms per formula unit.

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Site	Site population (a.p.f.u.)	Site scatter	ring (e.p.f.u.)	Mean bond	Mean bond length (Å)		
		Refined	Calculated	Refined	Calculated		
<i>T</i> (1)	3.21 Si + 0.79 Al			1.643	1.642		
T(2)	4 Si						
M(1)	$1.70 \text{ Mg} + 0.30 \text{ Fe}^{3+}$	28.64	28.20	2.067	2.070		
M(2)	$1.23 \text{ Mg} + 0.06 \text{ Fe}^{2+} +$	29.10	28.61	2.058	2.034		
	$0.43 \text{ Al} + 0.27 \text{ Cr} + 0.01 \text{ Ti}^{4+}$						
<i>M</i> (3)	$0.83 \text{ Mg} + 0.12 \text{ Fe}^{2+} + 0.05 \text{ Li}$	13.67	13.23	2.083	2.085		
Sum C cations	-	71.41	70.04				
<i>M</i> (4)	1.22 Ca + 0.78 Na	33.34	32.98				
A+A(m)+A(2)	0.85 Na + 0.04 K	10.72	10.11				
O(3)	$1.67 \text{ OH} + 0.03 \text{ F} + 0.30 \text{ O}^{2-}$	16.30	16.03				

TABLE 7. Site populations in katophorite AMNH H32734.

e.p.f.u. - electrons per formula unit; a.p.f.u. - atoms per formula unit.

which is, however, consistent with crystallization in volcanic rocks or in mantle xenoliths.

The paragenesis of katophorite associated with jadeitite has been interpreted as a stage in the progressive metasomatic reaction between jadeitite-forming fluids and serpentinizing peridotite. The fluid forms veins in the serpentinite during a period of subduction followed by exhumation (Shi et al., 2012: Tsujimori and Harlow, 2012: Harlow et al., 2014). Amphibole formation apparently changes from katophorite to nybøite to eckermannite and glaucophane as a function of admixing components of jadeitite, serpentinite and a Na- and Al-rich hydrous fluid at high pressure and low temperature (~≥1 GPa at 300-400°C: Shi et al., 2012). Modest Li enrichment has been reported in jadeite from jadeitites, particularly from Myanmar and Guatemala (up to 123 ppm: Sorensen et al., 2006; Simons et al., 2010), which is consistent with the Li content inferred from the low sitescattering value obtained in this study at the M(3)site.

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